

Chapter Four: Hyperspectral imaging in Long Valley Caldera: Tracking volcanogenic CO₂ and its lethal effects

1.0 Introduction

In May 1989, a small magnitude earthquake swarm hit the east-central region of the Sierra Nevada in the state of California. The swarm was located beneath the Pleistocene-aged Mammoth Mountain - a rhyodacitic stratovolcano located on the southwestern rim of the much larger, 760,000 year-old Long Valley caldera (Figure 4-1). Early earthquakes of the swarm were probably due to magmatic dike intrusion at depth (Hill et al., 1990) and recent relocations by Prejean (2001) indicate magma movement from initial depths of 7-9 km to within approximately 1 km of the mountain's surface over that six month time period.

The following spring (1990), an unusually heavy loss of needles was observed at several places on Mammoth Mt. by U.S. Forest Service personnel (Farrar et al., 1995), especially surrounding the popular recreation area of Horseshoe Lake. Approximately 4 ha of trees were dead at this lake alone, affecting all species of trees and other forest vegetation. Their deaths were initially attributed to the Sierran drought of the 1980's. In 1994 however, soil gas measurements made by the USGS confirmed that the kills were likely due to asphyxiation of the vegetation via the presence of 30-96% CO₂ in the ground around the volcano (Farrar, 1995). Current flux estimates for the entire mountain are approximately 300-500 tons/day, while flux at the Horseshoe Lake tree-kill is 93 ± 22 tons/day (Rogie, 2001). Background concentrations of CO₂ in this region are approximately 360 ppm, however concentrations in tree-kill zones can be upwards of 10,000-100,000 ppm

early in the day (Rogie, pers. comm., March 2000). Many areas of CO₂-induced kills are now identified on Mammoth (Figure 4-2).

Traditional mapping of CO₂ discharge zones on Mammoth Mt. is done on-foot with portable accumulation chamber instruments and GPS. The remote sensing techniques described in this study are accomplished remotely, making the spatial and temporal mapping of volcanogenic-assisted forest deaths easier and quick to do. Such mapping is vital for geological, forest, ski, and city personnel in charge of determining areas and level of hazard at Mammoth Mt. This study attempts to utilize the superior calibration and fine spectral sampling of Advanced Visible/Infrared Imaging Spectrometer (AVIRIS) to identify and map the characteristic spectral absorptions of CO₂ gas within the near-infrared portions of the electromagnetic spectrum (2.00-2.50 μm). The following sections address the genesis of the tree-kills on Mammoth and initial efforts at detection and mapping of anomalous CO₂ in the atmospheric column above Mammoth Mt.

2.0 Background

2.1 Mammoth Mt. and volcanogenic CO₂-induced tree-kill

Tree morbidity was first linked conclusively to massive CO₂ exhalation by Farrar et al. (1995). Other workers have detailed the likely volcanogenic source of CO₂; its paths of diffusion, generation, chemistry, behavior in the near subsurface, surface and air; spatial distribution of flux zones; temporal flux behavior; and dependency on local climatic variables (Sorey et al., 1998, 1999; McGee and Gerlach, 1998; Gerlach et al., 1999; Rogie et al., 2000, 2001). It is difficult to explain the large volume of gas currently fluxing from Mammoth with only the 1989 intrusion.

Instead, Sorey and others suggest that CO₂ travels up along pre-existing faults and fractures from a semi-sealed, low temperature, gas reservoir that caps a much hotter liquid reservoir heated at depth by a magma chamber(s) fed by many years of intrusions. The gas in this semi-sealed chamber is 99% CO₂ and 1% N₂. Sustained low magnitude seismic activity breached this low permeability seal in 1989, leading to massive cold CO₂ exhalation along the pre-existing faults and fractures on and around Mammoth Mountain. This process is shown schematically in Figure 3. C and He isotopic ratios are consistent with a magmatic source for the CO₂ gas (Sorey et al., 1998), although additional CO₂ could also be produced from contact metamorphism of old Paleozoic carbonate-bearing roof pendants that crop out around Mammoth and presumably also at depth (Sorey et al., 1998). Recent work by Rogie et al. (2000) indicates that current CO₂ gas flux is > 95% magmatic in origin. Current estimates of whole-mountain CO₂ flux are 200-300 t/d (Sorey et al., 1999), while the flux at Horseshoe Lake alone is approximately 100 t/d (Rogie et al., 2000).

The Horseshoe Lake Tree-kill lies on the southern flank of Mammoth Mountain atop Quaternary andesites, dacites, and glacial tills. However, the subset of the kill analyzed in this study lies entirely on glacial till deposits. The dominant tree species in the Horseshoe Lake region is *Pinus contorta* (Lodgepole pine). Other species include *Abies magnifica* (Red Fir), *Tsuga mertensiana* (Mountain Hemlock), and *Pinus albicaulis* (Whitebark Pine). Initial measurement at this tree-kill by Farrar et al. (1994) led to estimates of 1200 tons/day of CO₂ diffusing from the ground from a single sample location. Present day multi-spatial, multi-temporal measurements indicate a reduced average flux rate of 100 tons/day (Rogie et al., 2000). The higher

flux rates of 1994 are probably indicative of undersampling, and the recently reported lower rates are probably closer to the current flux state of the volcano. Though the CO₂ is fluxing diffusively from a large area around Horseshoe, its initial source is probably a fault or series of faults related to Bailey's Horseshoe Lake Fumarole Fault (HSLF on Figure 3-3) (Bailey, 1989). The CO₂ travels up along this fault(s) and diffuses into the soil when it reaches a certain depth. During the winter months, snow may behave as a dense soil layer, allowing the CO₂ to flux from areas of higher permeability in the snow, while trapping the CO₂ in other areas. Extensive studies of the temporal and spatial variability of CO₂ flux were done by Rogie and others since 1997 (Sorey et al., 1999; Rogie et al., 2000; 2001).

2.2 Spectroscopy of CO₂

Gas absorptions form primarily in response to vibrational absorption processes. For CO₂, there are nine fundamentals (vibrational modes). The stretching and bending of the bonds in the internal modes produces the infrared absorptions seen in CO₂ spectra. In addition, when CO₂ makes a vibrational transition, it usually makes a rotational one as well. CO₂ thence has three vibration-rotation bands (two of which are the same frequency) and a fourth band that is infrared inactive. Other absorptions are seen in CO₂ spectra, and these are due to overtones and combinations of the original fundamentals. The near-infrared absorptions of interest in this study are combination bands centered around 2.0 μm. They have centers at 1.96 μm, 2.01 μm and 2.06 μm. Each absorption is actually a doublet. The main absorption feature of interest used in this study is the 2.06 μm band whose doublet lays longward at 2.08 μm (Figure 3-4). Intensity of absorptions are affected by both the level of fundamental mode (fundamentals have higher

intensities of absorption than overtones and combinations do) (Gaffey et al., 1993), and the relative amount of the material causing the absorptions (the total absorptance increases with the amount of material present)(Schurin and Ellis, 1968). Widths of bands are greatly affected by temperature and pressure, with increasing values causing absorptions to widen.

3.0 AVIRIS analysis

3.1 Spectral detection of anomalous CO₂

The analysis goal was to determine whether anomalous levels of CO₂ are detectable in the atmospheric column using AVIRIS radiance data. Two separate years of AVIRIS data were utilized in this study; 1996 and 2000. Scene boundaries were chosen to encompass the massif of Mammoth Mt. as well as some outlying regions known to be volcanically active in the recent geologic past. Boundaries for both the 1996 and 2000 AVIRIS scenes are shown in Figure 4-1.

Both years of data were subjected to the same analysis methodologies. The data were spatially subset, spectrally subset, and analyzed for unique, repeatable, spectral features in the 2.0 μm CO₂ absorption wavelength region. In the wavelengths measured by AVIRIS, there are three CO₂ absorption regions: 1.4 μm , 1.6 μm , and 2.0 μm . This study was limited to analysis of the absorptions centered around 2.0 μm as the 1.4 μm absorptions lie too close to the H₂O absorption maximum at 1.38 μm , and the shallow 1.6 μm absorptions were not discriminated from background noise. Though the 2.01 μm feature has the highest absorption intensity, we chose the 2.06 μm absorption feature (seven bands spanning 2.04-2.10 μm). We found it to be less vulnerable to contamination from the wings of the strong 1.87 μm H₂O band. All major and minor water bodies were masked before any

spectral analysis. This was done both to reduce the spectral variability encountered in the scene and to reduce the effects of the 1.87 μm water band on the 2.06 μm CO_2 absorption

Continuum Removal (CR) and Minimum Noise Fraction (MNF) processing were applied to both years of AVIRIS data. We theorize that anomalous levels of CO_2 degassing from Mammoth Mt. will be detectable above background levels. Band depths in regions of elevated flux will be higher than expected given a certain elevation. Those regions with deeper than expected absorptions are possible point sources of magmatic CO_2 degassing. Normal CO_2 at these elevations is approximately 360 ppm, which is approximately 0.04% of the gasses in the atmospheric column measured by AVIRIS. Minor concentration variations from 360 ppm are difficult to measure (Green, 2002). However CO_2 concentrations at several locations on Mammoth Mt. reach levels of 10,000 – 100,000 ppm. It may be possible to detect CO_2 concentrations approaching 10 % in the atmospheric column.

3.1.1 AVIRIS analysis: Continuum Removal

CR was performed on the 2.06 μm absorption feature region in both years of AVIRIS radiance data. Theoretically, the more CO_2 there is in the atmospheric column, the deeper this absorption feature will be. Since there is a direct correlation between the amount of a gas and the relative depth of its absorption, a CR applied to the data should reveal those regions in an image dataset with higher amounts of CO_2 in the atmospheric column. Deeper absorptions should relate to increased levels of CO_2 , while more shallow absorptions should relate to decreasing levels of CO_2 . Differing depths of absorption were delineated with an arbitrary density slice of the final CR image.

3.1.2 AVIRIS analysis: Minimum Noise Fraction

The second analysis performed was the MNF. The MNF is basically two cascaded principle component transformations, where the first transformation decorrelates and rescales the noise such that the noise has unit variance and no band-to-band correlations, and the second transform takes the noise whitened data and puts it through a standard Principle Components calculation. The MNF transformed data were analyzed on an image-by-image basis where each coherent image may emphasize a particular class of material. By focusing in on a particular absorption (2.06 μm), it was hoped the material causing said absorption would be represented in one of the coherent MNF images.

4.0 Results

4.1 AVIRIS analysis: Results

Figure 4-4 shows the results of the CR with an eight level density slice applied. The deepest absorptions are shown in red. The next deepest are shown in green, then blue, yellow, cyan, magenta, maroon, and seagreen respectively. An elevation effect should be discernable in the data: higher elevations should have less overall CO₂ and a shallow CO₂ absorption feature while lower elevations should provide a much deeper absorption feature due to the increased amount of CO₂ in the atmospheric column (Green, 2001). Mammoth Mt. located in the lower southeast corner of the image rises approximately 600 m above the surrounding landscape. As such, higher elevations of the mountain are colored in green, blue, yellow, etc. while surrounding terrain is colored red. The blue coloration on the summit of the mountain indicates a more shallow absorption than the red coloration on its flanks,

which indicates a deeper absorption. The CR algorithm appears to work at this regional scale, however regions known to host anomalously high CO₂ flux levels are not identifiable on this CR image. Average spectral signatures extracted from each density class show an expected pattern of deeper absorptions for lower elevations and more shallow absorptions for higher elevations (Figure 4-4). Also of note, though the main absorption is located at 2.06 μm , CR analysis has brought out an absorption centered at 2.08 μm . Its depth appears to be conversely related to elevation, i.e. the higher elevations have a deeper 2.08 μm absorption than the lower elevations. This is opposite to the absorption depth/elevation relationship for 2.06 μm .

The results from the MNF analysis are more compelling than that achieved with the CR, however they are more complex. Four of the seven bands analyzed in the 2000 imagery were coherent, while only three of the seven bands were coherent in the 1996 imagery. In the 2000 AVIRIS image, MNF band 3 appears to contain a spatial distribution of degassing CO₂, while in the 1996 AVIRIS image, it's MNF band 2 that reveals a CO₂ distribution similar to that known to exist from previous field studies (Sorey et al., 1998; Rogie et al., 2001). Figure 4-5 shows results from the MNF analysis of 2000 AVIRIS imagery. A density slice was applied to MNF band 3. The most extreme values of the MNF (i.e. the highest density slice) were then isolated and highlighted. These areas are plotted on top of the georectified MNF band 3 image along-side mapped faults of the region.

Results from the MNF analysis on 1996 AVIRIS imagery produced similar distributions as those seen in the 2000 imagery. There are some high MNF value zones not seen in the 2000 imagery, as well as zones identified in the 1996 image

that do not appear in the 2000 image. Figure 7 shows both years of extreme MNF-value zones. The zones appear around the mountain, occurring on varying rock types, differing elevations, and in both tree-covered and tree-less landscapes.

5.0 Discussion: Feasibility and problems with anomalous CO₂ detection and mapping

The general success of the CR analysis in mapping gross amounts of CO₂ in the atmospheric column is encouraging. However, the inability to map regions of extremely high concentrations of CO₂ at several major tree-kill sites with a simple CR analysis was disappointing. One problem may be that the CR/density slice analysis only measures the depth of the 2.06 μm absorption at its maximum minima. The prominence of the 2.08 μm absorption longward of the main 2.06 μm absorption may hold the key to part of the problem. This 2.08 μm absorption is probably the second half of the 2.06 μm doublet. The fact that it appears to be sensitive to elevation in a converse way to the 2.06 μm absorption is undoubtedly important. A CR analysis of just this absorption (3 bands centered on 2.08 μm) may reveal a more compelling CO₂ flux zone pattern. Another way to investigate the 2.06 μm absorption may be an area-of-absorption analysis. The calculation of band depth normalized to absorption feature areas is found to closely follow amounts of plant biochemical constituents such as water, chlorophyll, cellulose, sugar, etc. (Kokaly and Clarke, 1999; Curran et al., 2001). Perhaps similar area calculations would prove viable for CO₂ gas absorptions.

The MNF results are quite compelling, though poorly constrained. We cannot know exactly what the MNF is detecting. It is mapping levels of coherence, but the classes produced from this procedure do not possess unique spectral signatures like

other endmember classes we are used to. We initially assumed that extreme values of MNF band 3 (2000 data) were detecting anomalous levels of CO₂ via a deeper 2.06 µm absorption relative to surrounding pixels containing more shallow absorptions in this wavelength region. We theorized that these deepest absorptions were different enough from neighboring pixel values, that they produced their own MNF coherence band. The resulting spatial distributions of the extreme MNF values for both 1996 and 2000 are almost perfect matches to known zones of volcanogenic CO₂ flux, some of which host tree-kill sites. However, there are a few exceptions, which may hold the key to determining what the MNF transform analysis is actually detecting.

There are two major sites in the 2000 image mapped as extreme in MNF band 3 that do not correspond to any known zones of CO₂ flux or CO₂-induced tree-kill sites. These include zones mapped in the Rainbow Fire kill of 1992 and zones mapped at Chair 2 on the northern flank of Mammoth in-bounds of the ski area. Groundtruthing with a portable gas accumulation chamber in July, 2002 at these two sites revealed no anomalous CO₂ flux. However, both sites contained an excess of cellulose and lignin in the form of dead trees (at the Rainbow Fire site) and dry mulching grass (spread over the ski-runs at Chair 2 to increase slope stability). The grass possesses a good deal of cellulose, while the dead trees contain both cellulose and lignin within the bark and wood.

The biochemicals cellulose and lignin have several distinctive absorptions, one of which is centered on 2.10 µm (Figure 4-7A). The 2.06 µm CO₂ absorption lies on the shortward wing of these broad biochemical absorptions (Figure 4-7B). If you only look at straight reflectance data, the lignin/cellulose absorption doesn't appear

capable of greatly affecting spectral analysis. However, analysis of the data included spectrally subsetting the image to only seven bands around the absorption, and CR processing. If we apply the same analysis steps to the spectra of lignin and cellulose, prominent absorptions are revealed at 2.06 μm (Figure 4-7C).

This suggests that the presence of excessive dead trees and grass may create a landscape that would be preferentially mapped when using a density sliced, directed MNF transform of the 2.06 μm absorption. Most CO_2 flux zones on Mammoth have an abundance of dead or dying trees accompanying them. Perhaps the MNF analysis described in this paper is merely mapping cellulose/lignin in the form of dead trees associated with volcanogenic CO_2 emission zones. However, there is one problem with this scenario. There are a myriad of other dead tree areas on and around Mammoth measured by AVIRIS that are not highlighted with the directed MNF analysis of the 2.06 μm absorption. These include large areas of trees killed by avalanche, flooding, snow and trash burial, and insect infestations. This result suggests that there is something unique about the dead tree cellulose/lignin absorptions highlighted with the MNF analysis in this paper. Perhaps the MNF analysis is capturing both sources of absorption, i.e. the cellulose/lignin absorption from the dead trees and grass is adding into the anomalous CO_2 absorption. We currently can't constrain how much of each spectral endmember is adding into the final spectral signature. What is unequivocal, is the creation of a map of volcanogenic CO_2 flux zones far surpassing those previously created, in detail and completeness, using standard surveying techniques.

6.0 Conclusions

Multi-temporal air photo analysis has revealed new spatial and temporal patterns of the CO₂-induced Horseshoe Lake tree-kill. The success of this analysis at Horseshoe indicates that similar analyses on other parts of Mammoth, would be an efficient way of determining the temporal growth of the kills as a whole. Our attempts at detecting and mapping anomalous volcanogenic CO₂ in the atmospheric column produced compelling spatial distributions of CO₂ flux zones that matched quite well with known, previously mapped flux zones. However, this analysis is ultimately complicated by an unknown relationship between CO₂ absorptions and those absorptions from plant biochemicals. Further work aimed at quantifying this relationship should be undertaken.